A Garp3 Model of Environmental Sustainability in the Danube Delta Biosphere Reserve based on Qualitative Reasoning Concept

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Abstract

The paper presents a qualitative reasoning (QR) model of sustainable development issues of the Danube Delta Biosphere Reserve (DDBR, Romania) environmental system. This model contributes to NaturNet-Redime projects goal to assist the implementation of the EU's Strategy of Sustainable Development. The DDBR QR model emphasizes the main causes that hamper achievement of sustainable development in the DDBR. Specifically, following a standardized framework for conceptual description of QR case studies, we have organized our expert knowledge about negative effects of water pollution from the Danube catchment area on aquatic biota and human health in and around the DDBR. We present essential background about the model system, and describe how available knowledge was encapsulated into QR knowledge structures including model fragments and scenarios. Finally, we present simulation output based on this knowledge and discuss how this output contributes to understanding factors affecting sustainability of the DDBR.

Introduction

Qualitative Reasoning is of great importance for developing, strengthening and further improving education and training on topics dealing with systems and their behaviors (Bredeweg and Forbus 2003). To meet the objectives of the European Union's Strategy for Sustainable Development (SSD) that call for increasing participation in the process of making decisions that affect sustainable development (SD), stakeholders, decision makers, and citizens must gain a better understanding the factors that affect SD (European Commission 2001). SD is broadly defined as "a real increase in well-being and standard of life for the average person that can be maintained over the long-term without degrading the environment or compromising the ability of future generations to meet their own needs" (Brundtland and the World Commission on Environment and Development 1987, Cunningham and Cunningham 2005).

Part of the FP6 NaturNet-Redime project involves developing qualitative reasoning (QR) models of five case studies that explore different SD issues and scenarios, in order to support these objectives of the SSD. The goal is to represent SD problems from different systems and perspectives and build an online curriculum about SD that focuses on user interaction with QR models.

Both to support the model building effort as well as to facilitate integration of the different models, Bredeweg et al. (2006) developed a "structured approach to qualitative modeling". Researchers from five case studies (the Danube Delta Biosphere Reserve, Romania; Riacho Fundo, Brasil; River Mesta, Bulgaria; Salmon restoration in England, and river catchment restoration in Austria) have been following this methodology.

The goal of this paper is to present a description of the DDBR model system, main model goals, the system global behavior, the main model ingredients as they are implemented into the Garp3 workbench (representative **scenarios** and **model fragments**) and the scenario simulation results. The QR models will be used by end users for learning about specific conditions to be fulfilled by the modeled system (either social, economic, or environmental) in order to contribute to increased public involvement as called for in the Strategy for Sustainable Development.

Model System

The DDBR - located at the mouth of the Danube River before it reaches the Black Sea - was declared as a World Heritage Site and Wetland of International Importance since 1990 (according to The Ramsar Convention on Wetlands, signed in Ramsar, Iran, in 1971). Its area of 5,800 sq. km, making it one of the greatest wetlands in the world, contains 30 types of terrestrial and aquatic ecosystems, of which 23 are natural or artificially modified and 7 are man-made ecosystems, including human settlements (Oosterberg et al. 2000). The DDBR's status as a biosphere reserve dictates that all social and economic actions must fall in line with **biodiversity conservation and protection measures**. Thus, the most appropriate concept of sustainable development for DDBR can be expressed by development through biodiversity, where most flora and fauna species are protected both to meet obligations of international conventions, but also to serve as natural resources for social and economic development of the region.

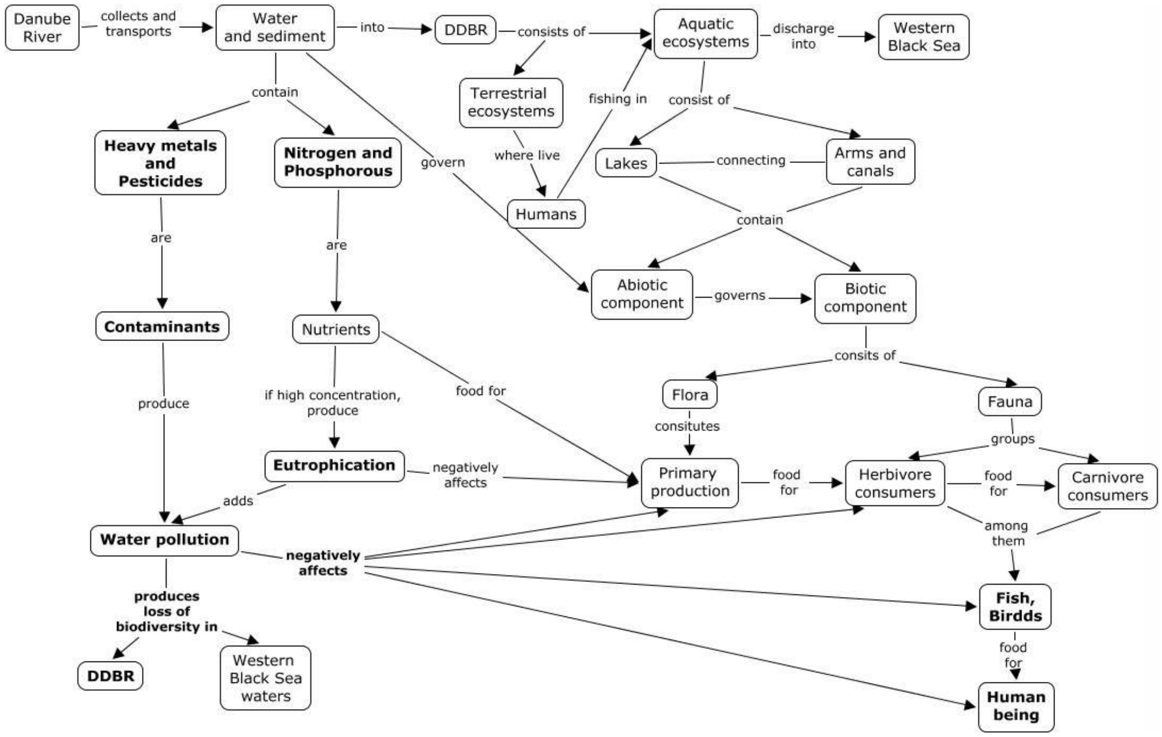


Figure 1. Concept map for Danube Delta Biosphere Reserve water pollution – the negative effect on DDBR biodiversity and human health.

Stakeholder Issues

Scientists from DDBR met with local stakeholders to determine threats to conserve and develop these resources within the DDBR. The stakeholders involved in DDBR management include: nature conservation and protection bodies (DDBRA, NGOs), fishery and fishing companies, tourism companies, fluvial and marine transport companies, and recreational hunting groups.

Stakeholders identified the following threats:

- Decline in biodiversity (number of species) over the last several decades
- Contamination of water and fish from pollutants
- Concern about contamination in humans
- Reduction of fish diversity and abundance.

Decline in biodiversity (Otel and Ciocarlan 2000) is most likely a direct result of loss of wetlands through embankment works for different types of land use (agricultural polders, fishponds, and forest plantations), summing 15% of the whole DDBR surface. This has reduced habitat for migratory waterfowl, an important draw for ecotourism. Contamination from water pollutants is also an important potential mechanism for threatening biodiversity in the DDBR.

Contamination of water and fish from pollutants also contributes to health problems in humans. Contaminants come in, basically, two forms: heavy nutrient loads from agricultural fertilizers and heavy metals from industry. In both cases, most of the pollutants originate from far upstream in the vast Danube River catchments. Heavy nutrient loads lead to algal blooms, which can result in toxic by-products form algae as well as depletion of oxygen in the water when algae die and are degraded by bacteria. This can cause die-offs in fish. Heavy metals in the DDBR waters threaten human populations in two ways, first from direct consumption because many people drink untreated water directly form the DDBR waterways, and second from consumption of fish which bioaccumulate heavy metals (Otchere 2003; Wachs 2000) in their muscle tissues.

Fishing has been the main occupation of the Danube Delta inhabitants since ancient times and although nowadays the supply of fish has diminished and changed in quality, it continues to be basic trade. Contamination is one of the causes of reduced fish diversity and population sizes, but also over-fishing (even poaching) has been recording especially within the last decades.

Model Specification

Before implementing the model in the Garp3 modeling workbench, we identified the main model goals, created a concept map to organize our thinking about processes, entities, and relations, and describe the kind of behavior we want the model to produce. These steps are described in the following subsections.

Main Model Goals

Contamination by pollutants is at the root of most of DDBR's threats to SD. Furthermore, in order to understand indirect as well as direct effects of pollutants on humans, their effects on other ecosystem components, like fish, must also be understood. Thus, the DDBR model will describe the aquatic ecosystems behavior governed by water pollution rate and the ways it propagates to aquatic organisms and to humans living in or around the DDBR. The main goal of the DDBR model is:

- Understand and emphasize connections between water pollution in the Danube River catchment basin and health of human population living in and around the DDBR.

The model will be used to explain and educate the environment agency representatives, decision makers and stakeholders about the working of processes within the Danube River and their influence on these processes. Also the model will be used for argumentation purposes to convince decision makers what kind of actions they should take in order to improve (or stop) the Danube River water pollution process.

DDBR Concept Map

The concept map helps identify, clarify, and focus our knowledge about the system of interest (Figure 1). The model for the DDBR case study should capture the most relevant problems mentioned by the stakeholders, as reflected in the model goals. Hence, the concept map stresses effects of water pollution process on the aquatic biological components and human health for people living inside or around the DDBR.

System Selection and Structural Model

The DDBR full structural model (Figure 2) contains both terrestrial and aquatic ecosystems. It depicts a broader perspective on the entities and relations between them in the DDBR. The subset of entities that is relevant to the model goal specified above are shown in bold in Figure 2. The main system entities to be included in QR are thus model ***Water***, ***Fish***, and ***Human***. They can relate to each other by the following configurations:

› Fish ***lives in*** Water
› Human ***eats*** Fish
› Human ***drinks*** Water

Global Behavior

The main physical, physical-chemical and biological processes, influencing aquatic organism group behavior, in the framework of their Functional Feeding Group relationship, and humans (living in or around DDBR) are:

› water flow
› water eutrophycation – as result of Nutrients (mainly Nitrogen and Phosphorous compounds) increase
› phytoplankton bloom - overgrowth of algae and cyanobacteria (most of them are poisoning species)
› water pollution - mainly with nutrients, heavy metals, and cyanobacteria
› fish growth
› human being health.

Changes (increase/decline) in some groups influence other groups behavior. These cause-effect dependencies (Influence: I+/I- or Proportionality: P+/P-) for the aquatic ecosystems of the DDBR are presented in Figure 3).

In total, 12 processes are active in the DDBR aquatic environment that influences the abundance of each organism group. Changes in these abundances propagate to other quantities that affect other organism groups. Additionally, there are two agents (external influences) in

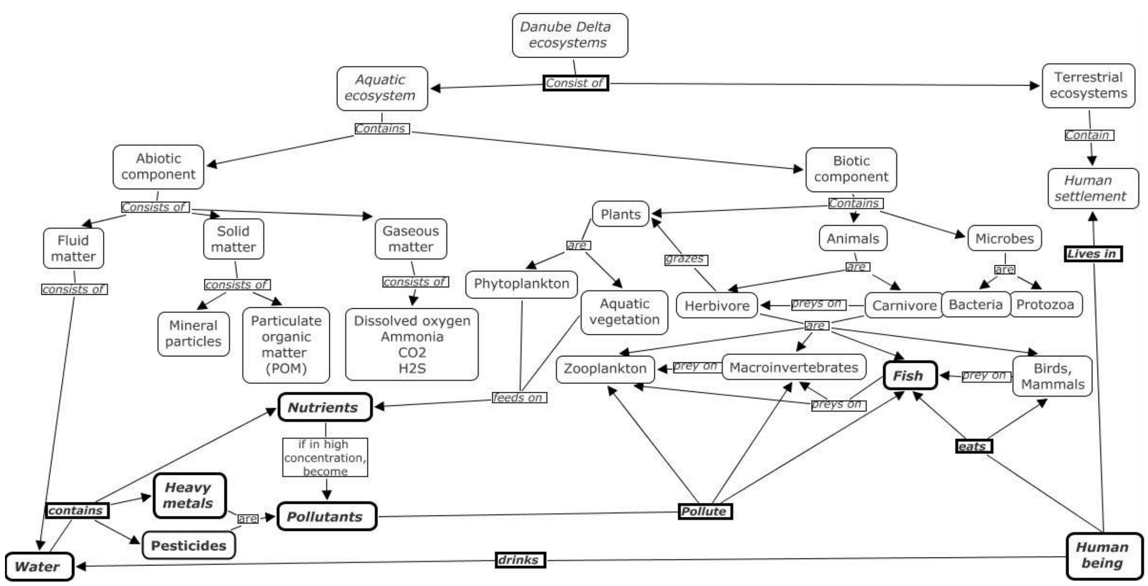


Figure 2. Structural model of the Danube Delta Biosphere Reserve aquatic ecosystems (Note: The structural entity hierarchy related directly to water pollution is represented in **bold**).

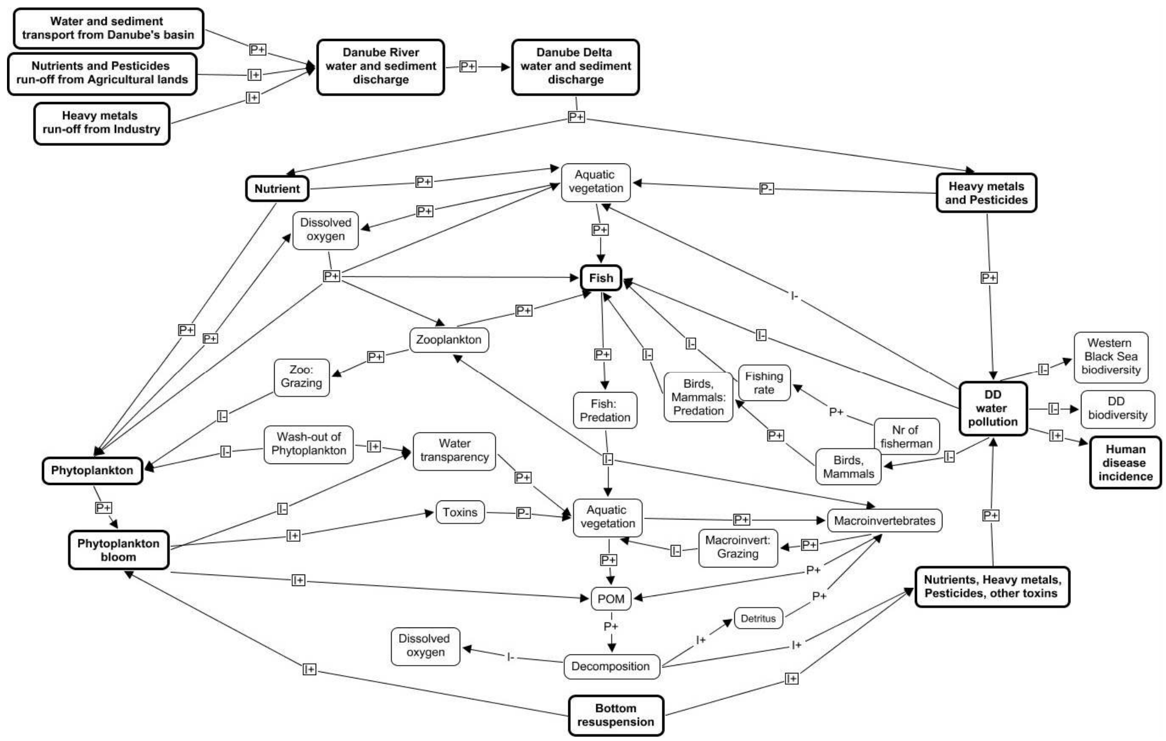


Figure 3. Global Causal model for Danube Delta Biosphere Reserve aquatic ecosystems water pollution.

the system: runoff from agriculture in the form of nutrients and runoff from industry in the form of heavy metals. These are considered external influences because they impact the DDBR system, but are located far upstream in the Danube catchment area. The implementation of these processes and agents can be seen in the section below on model fragments, and the context in which they operate in a simulation can be seen in the section on simulation results (below).

Space precludes a full description of details concerning the quantities that characterize each entity, as well as the quantity spaces that depict their qualitative values. These are discussed as they arise in the next sections describing scenarios, model fragments, and simulation results (see Cioaca et al. 2007 for full documentation).

Implementation details

QR model ingredients **implementation details** contain the detailed description of the modeled system: *Entities*, *Attributes*, *Configurations* (structural relationships between Entities), *Quantities* associated to each *Entity*, Quantity Spaces associated to *Quantities*, Scenarios, *Model Fragments*, *Agents* (External influences), and *Assumptions*. The main DDBR QR model ingredients are: 18 entities, 17 Scenarios, and 57 Model Fragments.

Figure 4 gives an overview of the entities involved in the model, and their hierarchical organization.

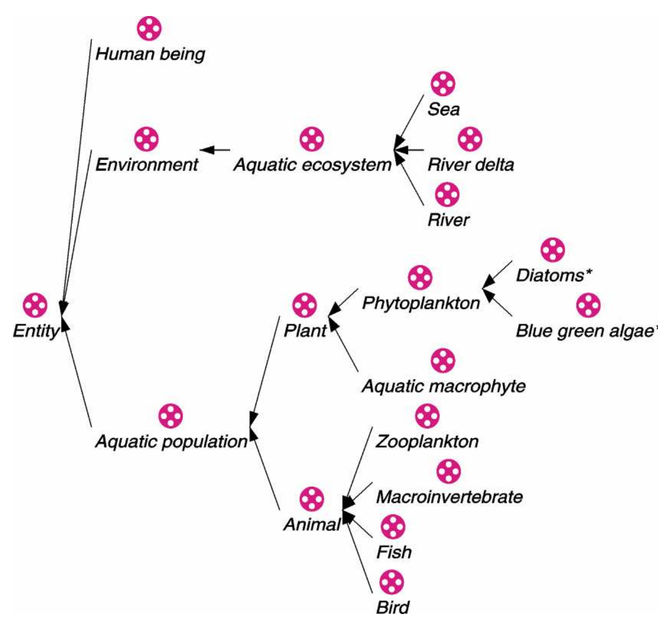


Figure 4. *Entity* hierarchy of the DDBR system.

Table 1 describes each of these entities and Table 2 describes configurations that are possible between entities.

Table 1. DDBR Entity summary.

Entity	Description
Human being	Human population living in/around the DDBR.
Environment	Physical space where aquatic ecosystems (***River***, ***River Delta***, and ***Sea***) belong to.
Aquatic population	Any biological entity living in water.
Aquatic ecosystem	A type of ecosystem where aquatic populations live.
River	Aquatic ecosystem where water flows from a catchment area to the sea.
River Delta	Aquatic ecosystem near the mouth of a river, consisting of branches, canals, and lakes.
Sea	Aquatic ecosystem at the end of a river and river delta.
Plant	This group is made of green plants (***Aquatic macrophytes, Phytoplankton***), organisms able to produce their own energy using sunlight to convert carbon dioxide and water into sugars by photosynthesis. ***Nutrients*** are their main food resource. Plants are the primary producers in all food chains since the materials they synthesize and store are the energy sources for all other organisms.
Animal	This group is made of all animals: ***Zooplankton***, ***Macroinvertebrates***, ***Fish***, ***Birds,*** and *Mammals*. They can be either herbivores or carnivores, and all are heterotrophic organisms (consumers) because they obtain their energy from other organisms (either plants or other animals).
Phytoplankton	Microscopic plant species (algae and bacteria) free-floating in the upper layer of water surface since sunlight is vital for their growth. Phytoplankton is the basis of most aquatic food chains, and also release oxygen into the water.
Aquatic macrophyte	Larger aquatic plant species; food resource for large animal species.
Diatoms	Predominant and harmless algae species division of Phytoplankton. Diatoms are a significant source of food for higher trophic levels, especially for *Zooplankton*.
Blue-green algae	Bacteria species (not algae), actually named as Cyanobacteria. Like other phytoplankton, they photosynthesize Most of species contain cyanotoxins in their cells. These toxins contribute to pollution and mortality of other organisms if concentrations are high..
Zooplankton	Microscopic species of animals inhabiting entire water column; food resource for larger animals, especially for fish.
Macro-invertebrate	Macroscopic animal species inhabiting both the water column and the bottom sediment (benthos).
Fish	Vertebrate species inhabiting almost any type of aquatic ecosystem.
Bird	Vertebrate species inhabiting aquatic ecosystems or the very near areas.

Table 2. DDBR Configuration summary

Configuration	Entity (from)	Entity (to)	Description
Drinks water from	Human being	River Delta	Specifies the link between people living inside the study area which provides their water source.
Eats	Human being	Fish	Specifies the link between people living inside the study area which provides their main food source.
Feeds on	Zoo-plankton	Diatoms	Specifies the feeding relationship between two aquatic species. One of them is consumer (predator) feeding on the other one (the prey).
	Macro-invertebrates	Aquatic macro-phyte	
	Fish	Zooplankton	
	Bird	Fish	
Flows in	River	River Delta	Specifies direction of water flow.
	River Delta	Western Black Sea	
In catchment area of	Agriculture (Run-off of Nutrients) Agent	Danube River	Specifies the ways the Agents exert their influence on River.
	Industry (Run-off of Heavy metals) Agent	Danube River	
Lives in	Diatoms	River Delta	Specifies that these species are aquatic species.
	Blue-green algae	River Delta	

Scenarios

A scenario describes the scope of a system to be modeled. It includes the *Entities/Agents* involved in modeled process, *Configurations* between *Entities/Agents*, *Entity/Agent Quantities* with initial values, and *Assumptions* (if necessary). This structure shows a possible start situation of the modeled process from which changes in the quantity values can be triggered, describing certain behaviors of the system. Here we present two scenarios that provide an overview of this model as related to the model goals.

Scenarios Concerning the Water Pollution Process

This Scenario models the DDBR water pollution process, its negative effects and the ways it propagates to aquatic

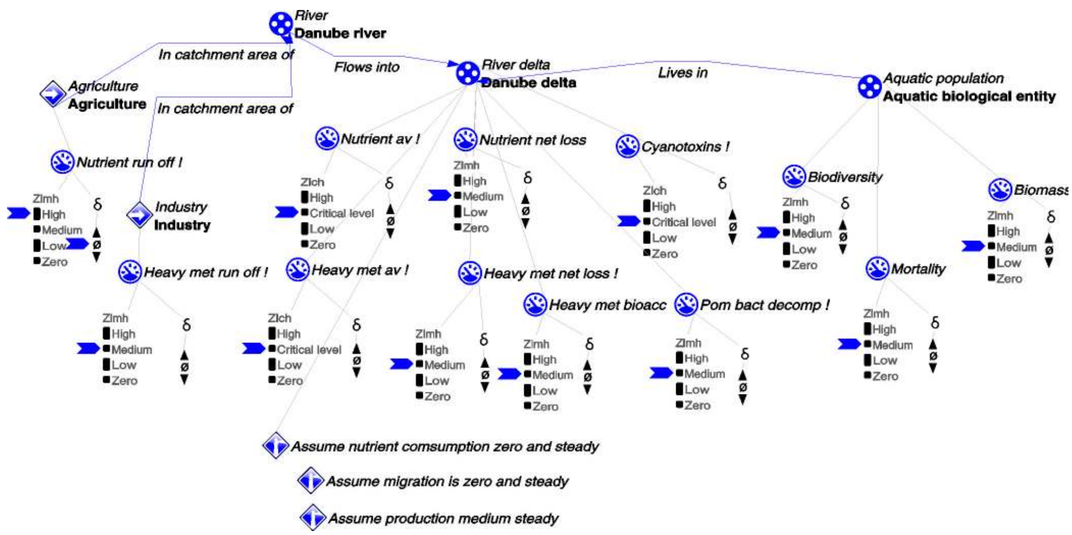


Figure 5. DD Water pollution and DD aquatic population biodiversity Scenario.

biotic component (Aquatic biological entities: Flora and Fauna populations) living in aquatic ecosystems of the modeled system. (Figure 5).

1. The modeled system's external influences (*Agents*) participating in this process are:
   - *Agriculture*: *Nutrient run-off* which participates in the water pollution process only if in high content. For values equal or smaller than Medium it participates in Plant growth process, as main food resource for any Plant species;
   - *Industry*: *Heavy metals*, which have the property of bioaccumulation in any aquatic biological entity, leading to that entity pollution, even Mortality if in Medium/High concentration in water.
2. The third water pollution component is given, mainly by *Cyanotoxins*. They are produced in water if there is a content of some poisoning species of Blue-green algae (Cyanobacteria), which contain Cyanotoxins in their cells.
3. To reduce the simulation complexity, Assumptions are introduced in the Scenario construction: "*Assume nutrient consumption is zero and steady*", "*Assume Migration is zero and steady*", and "*Assume Production is medium and steady*".
   ¤ It concerns the modelled system's components, Entities and their associated quantities, participating in the chemical process of Water pollution and the Configurations among Entities, as follows:
   ¤ The two system's Agents (External influences): Agriculture and Industry, developed "*In catchment area of*" the River, and participating in the system Water pollution with Nutrient run-off, and Heavy metals run-off, respectively;
   ¤ The River, that "*Flows into*" its own River Delta, after collecting and transporting the pollutants, mainly Nutrients and Heavy metals, from its catchmnet area;
   ¤ The River Delta system's inner components contributing to water pollution process: Nutrients, Heavy metals, Cyanotoxins, and POM bacterial decomposition.
   ¤ Aquatic population that "*Lives in*" the River Delta.

Scenario Concerning Human Health and Water Quality

This scenario models the effects of increasing heavy metal and nutrient concentrations in the DDBR on health of humans living in and drinking water from the DDBR waters (Figure 6). Initial conditions can be seen in this

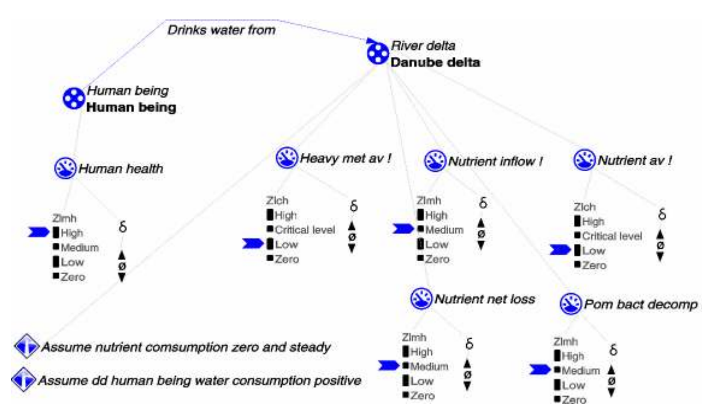


Figure 6. DD Human health influenced by DD water quality Scenario.

figure. Quantities related to nutrients and particulate organic matter are included only to satisfy certain static model fragments that require starting values for them, and are not of central focus for this scenario. Exclamation marks next to quantity names indicate exogenous behavior has been implemented (see Bredeweg et al. 2007). Hence, the amount of heavy metals in the environment (Heavy metals av) is set to low and exogenously increasing. This is meant to demonstrate the effects of increasing heavy metals on human health, after the factors contributing to increasing heavy metals (via runoff from industry) have been explored (see previous scenario). Other exogenous quantities set the respective quantity to remain steady (derivative = zero). Assumption labels implement behavior that is self-explanatory (Figure 6).

Model Fragments

There are three types of MFs: Static, Process, and Agent. Static MFs capture behavioral knowledge about the system. For DDBR aquatic ecosystems components there are 16 static MFs. A Process Model fragment defines the system behavioral characteristics related to a process. For DDBR system, there are 39 Process Model fragments. Two examples of Process Model Fragments are presented in Figure 7 and 8.

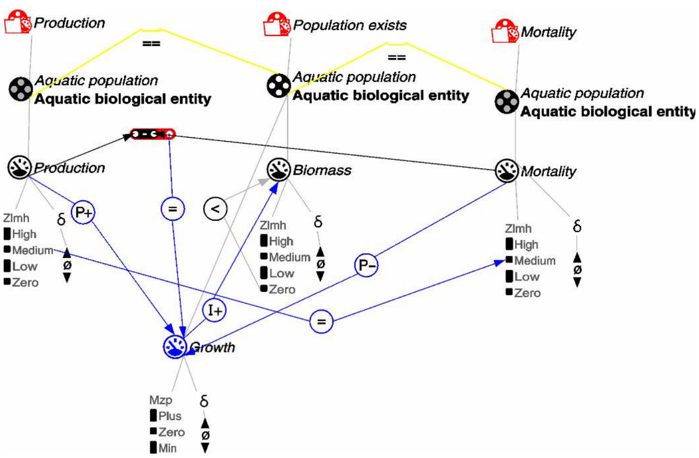


Figure 7. Aquatic Plant Growth - Process MF.

This MF (Figure 7) implements the causal dependencies (positive Influence I+, or positive/negative proportionality P+/P-) and the mathematical calculus (Minus, meaning difference between *Production* and *Mortality*) within any Aquatic population Growth process.

The MF shown in Figure 8 implements the structural and behavioral relationships between River delta and the Aquatic population, related to River delta: Water pollution influence on Aquatic population components behavior, as follows: positive influence (I+) on *Aquatic population*: *Mortality* and negative proportionality (P-) of *Aquatic population*:*Mortality* on *Aquatic population*: *Biodiversity*.

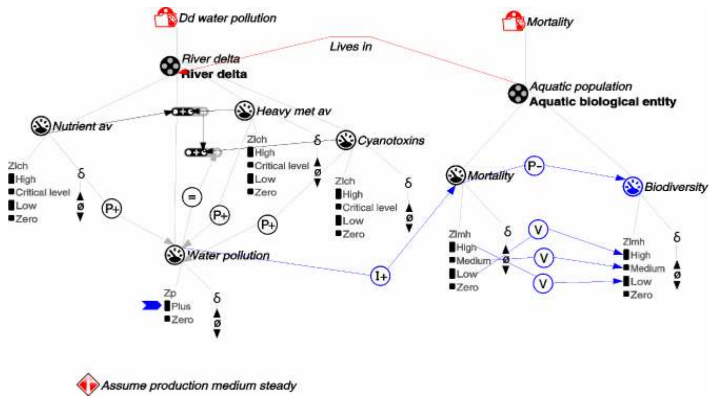


Figure 8. DD Water pollution and DD aquatic population biodiversity - Process MF.

Simulation Results

Scenarios' simulation results constitute the model output. This helps end users to understanding both the modeled system functional components causal relationships and the relevant factors affecting sustainability.

Simulation Results of Scenario Concerning the Water Pollution Process

There are presented simulation results for "DD Water pollution and DD aquatic population biodiversity Scenario" (see Figure 5). The most relevant results presented here are: Dependency diagram (Figure 9), Global State-graphs (Figure 10), and Global State-graphs and value history (Figure 11).

Dependency diagram

As the dependency diagram of any state in this simulation is very large, we present this diagram without quantity spaces (Figure 9). The diagram provides information on structure (entities, quantities, and configurations), causality (Influence I, or Proportionality P), and correspondence (Q, dQ) and in/equality (=, >, <) among the system's water pollutants (*Nutrients*, *Heavy metals* and *Cyanotoxins*), and any *Aquatic biological entity*:

Danube River: Nutrient inflow and Heavy Metals inflow main resources are the two system's external influences (Agents): Agriculture: Nutrient run-off and Industry: Heavy metals run -off, respectively, localized "In catchment area of" the River. There is a close relationship (P+, Q) between Nutrient run-off from Agriculture lands and Nutrient that enters the Danube River. The same relationship occurs between Heavy metals run-off from Industrial zones and Heavy metals that enter the Danube River. From the River, these two main water pollutants reach the Danube Delta aquatic ecosystems.

A part of *Danube Delta*: *Nutrient inflow* stays in the system and contributes to *Nutrient available for Plant* species growth while another part is lost (*Nutrient net loss*), either through *Nutrient outflow* or *Nutrient consumption* (by aquatic *Plant* species only).

The same happens with *Danube Delta*: *Heavy metals inflow*. The only difference is that a part of the *Heavy metals inflow* is lost (*Heavy metals net loss*) as they are bioaccumulated within any *Aquatic biological entity* body both of *Plant* and *Animal* species.

A part of *Nutrient net loss* and *Heavy metals net loss* is recycled from dead organic matter as result of Particulate Organic matter bacterial decomposition (*Pom bact decomp*) process.

Danube delta: Water pollution rate is the result of three main water pollutants: *Danube delta: Nutrient available*, *Heavy metals available* and *Cyanotoxins*;

Danube delta: *Water pollution rate* has a direct positive influence (I+) on any *Aquatic biological entity*: *Mortality*. That signifies that a positive rate of Water pollution process induces an increase of *Mortality* for any Aquatic population.

Aquatic biological entity: Mortality has an indirect negative influence (P-) on any *Aquatic biological entity: Biomass*.

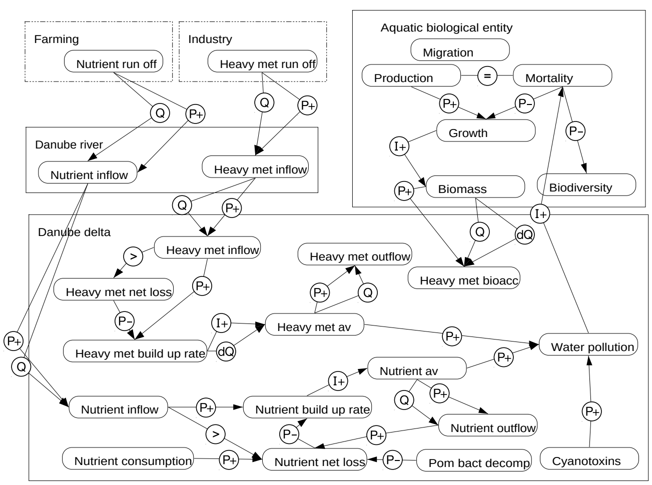


Figure 9. Dependency diagram (causal model) of the Water pollution process.

Global State-graphs

All states generated by full simulation, starting from the three initial states 1, 2, and 3 are presented in Figure 10. By full simulation of the initial states a total of 20 states are generated. Five of them are end-states: 12, 14, 15, 17, and 20.

Value history diagrams

Despite the many possible pathways resulting from the scenario, all of them show the same basic behavior with respect to heavy metals and biodiversity: heavy metals increase and biodiversity decreases (see right two value histories, Figure 11). Other paths differ only in behavior of nutrients, which may increase, decrease, remain constant, or exihibit a combination of these behaviors.

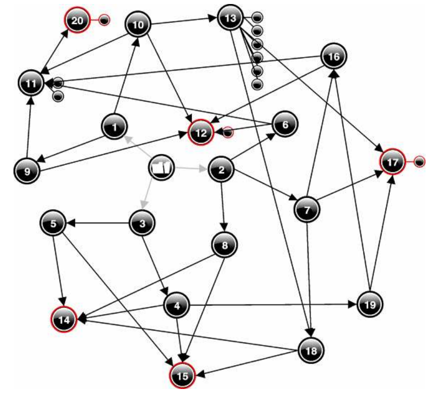


Figure 10. DD Water pollution and DD aquatic population biodiversity Global State-graph.

This is due to ambiguity in the relative magnitudes of inflow and outflow of nutrients (see end states, Figure 10 center). For example, states 15 and 20 define the end of the process, for two extreme conditions of the system as result of the *Danube Delta*: *Nutrient net loss*, High, + and Zero, 0, respectively.

Within the water pollution process related to *Aquatic biological entity* behavior, the *Aquatic biological entity*: *Biomass* never reaches the value Zero, because the *Growth* rate never reaches this value, as both the assumption and MF "*Growth on Migration only*", when Migration is assumed Zero/Steady, is not considered in this process. In these conditions, within most states, the following tendency happens:

1. Both *Aquatic biological entity*: *Biomass* and *Biodiversity* are Low, -;
2. *Aquatic biological entity*: *Growth* is Minus, -;
3. *Aquatic biological entity*: *Mortality* is High, +.

Simulation Results of Scenarios Concerning the Human Being Behavior from the Human Health Point of View

This simulation produces one possible beginning state, which gives rize to a total of 7 possible states and three behavioral paths (Figure 12). Each of these paths shows that as heavy metal and nutrient concentrations increase, human health decreases. Heavy metals increase because they were specified to increase due to an exogenous influence, whereas nutrients increase because nutrient inflow is greater than nutrient net loss (see Figure 13). The difference between the three paths arizes because of different relative rates of increase between heavy metals and nutrients.

Dependency diagram

The Dependency diagram for each of the states in the simulation is similar (Figure 13). The diagram shows how the model fragments have been composed into a complete causal model of the system specified by the scenario.

Figure 11. Value histories for beginning states (far left), end states (center left), and two behavioral paths (right) for the scenario concerning DDBR Water pollution and aquatic population biodiversity. →

It provides information on structural and causality (Influence I, or Proportionality P), correspondence (Q is a quantity space correspondence, dQ is a derivative correspondence, and V is a value correspondence) and In/equality (=, >, <) dependency relationships among the system's water pollutants (*Nutrient available* and *Heavy metals available*) and *Human being*: *Human health*.

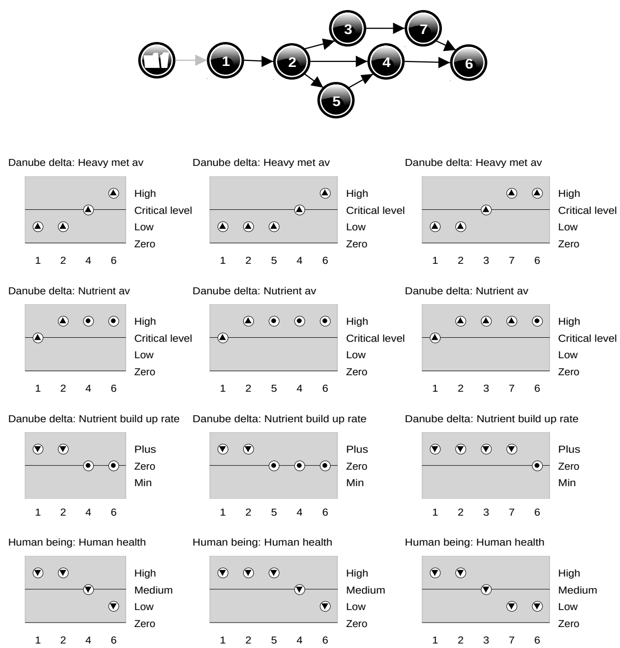
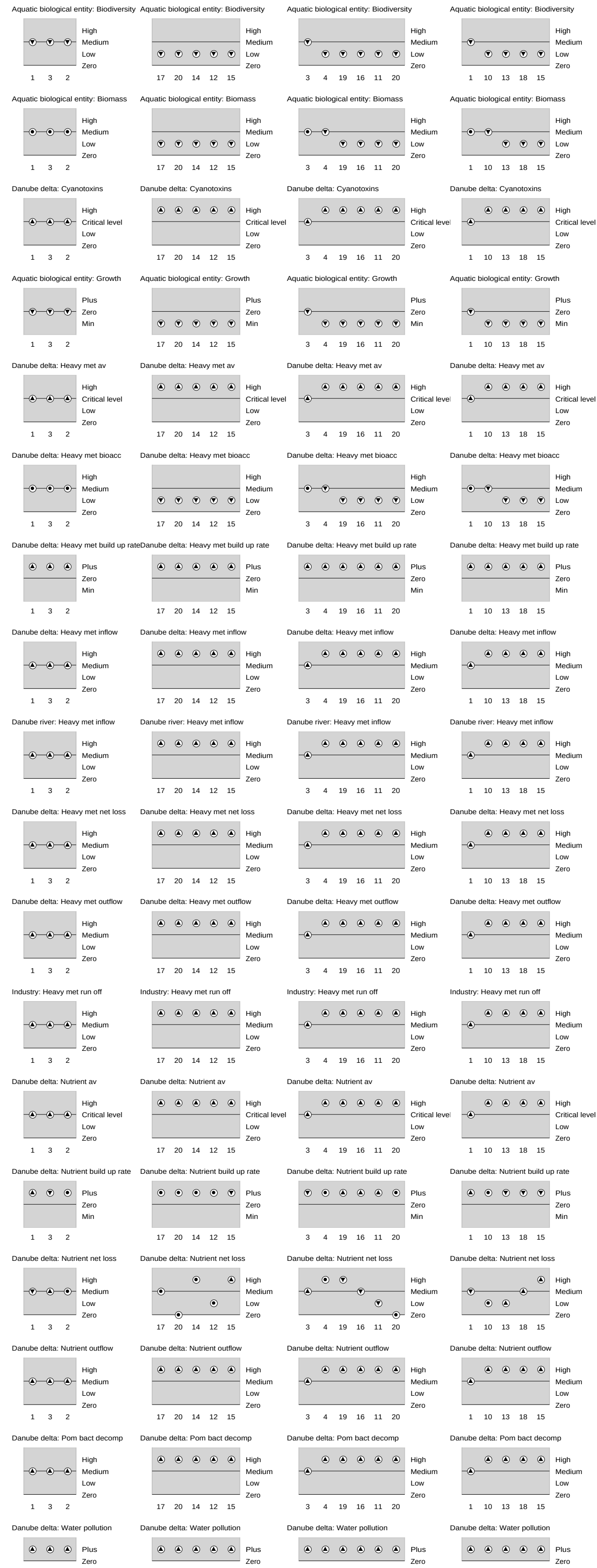


Figure 12. State graph and value histories for the three behavioral paths for scenario concerning human health and water quality. Quantities that were set to steady can be inferred from the scenario diagram (Figure 6).



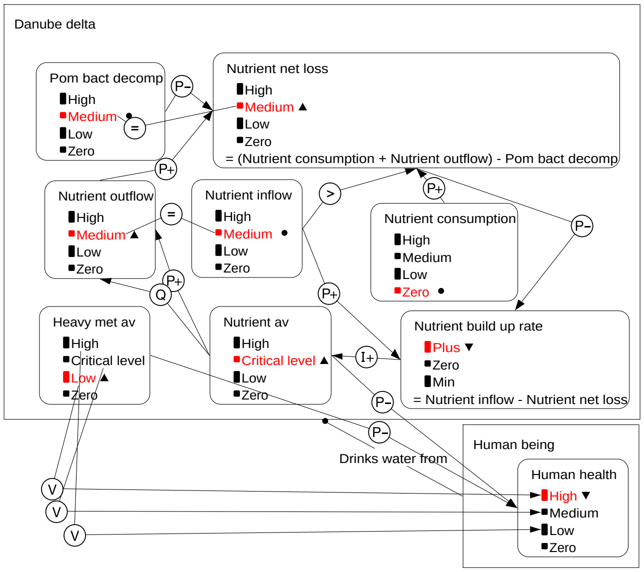


Figure 13. Dependency diagram for state 1 of the scenario concerning human health and water quality.

Discussion and Conclusions

This paper contains a description of some of the aspects of the DDBR Garp3 model, emphasizing the main causes and their effects that challenge achievement of Sustainable Development within the DDBR. The DDBR Qualitative Reasoning Model Fragments emphasize the causality conditions, which have been generating loss of DDBR biodiversity, aiming to delimit those objectives for a sustainable use of natural resources and a Sustainable Development Strategy addressing the aquatic ecosystems. Conservation and protection of biodiversity is one of the main objectives in achieving the Sustainable Development Strategy for the DDBR. These must be based on the best current understanding of the phenomena, which occur within and beyond the DDBR, including the whole hydrographic basin of the Danube River and the Western Black Sea coastal waters. Toward this aim, knowledge about the aquatic ecosystems behavior within DDBR system, as it is presented in the DDBR QR Model, serves for making decisions for biodiversity conservation and protection measures.

Ongoing work with this model serves to optimize the model-fragment representations to make the representations most insightful and capitalize on inheritance in the entity hierarchy more effectively. This will reduce the need to include extraneous quantities in some scenarios, while making the knowledge representation more transportable. Also, we are working to manage ambiguity through development of appropriate simplifying assumptions.

This model and accompanying documentation aimed at producing educational materials to teach about concepts of SD.

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